Current Status of One and Two-Dimensional Numerical Models: Successes and Limitations

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Abstract

The capabilities of one and two-dimensional numerical solar cell modeling programs (SCAP1D and SCAP2D) are described. The occasions when a two-dimensional model is required are discussed. The application of the models to design, analysis, and prediction are presented along with a discussion of problem areas for solar cell modeling.

Introduction

Accurate numerical models for single crystal silicon solar cells have proven to be very reliable in the simulation of the performance of these cells. These models have proven to be extremely useful in: the interpretation of experimental measurements; the identification of processes which limit cell performance; the prediction of benefits which will result from design and materials changes; the comparison of various cell designs; and the prediction of efficiencies which may eventually be obtained in silicon solar cells as various technological barriers are overcome.

The capabilities of a one-dimensional (SCAP1D) and a two-dimensional model (SCAP2D) are described and examples of their use for each of the above purposes are given.[1-3] It will be shown that there are circumstances under which cells which appear to be one-dimensional require a two-dimensional model to properly simulate their behavior.

As cells become more efficient the requirements on the accuracy of the physics used in the model become more stringent. Effects which are of little significance in poor or moderately good cells can take on major significance in high efficiency cells. A number of problem areas which are of concern in the modeling of high efficiency cells are discussed. These include heavy doping effects, metal-semiconductor boundary conditions, minority carrier mobilities, high injection lifetimes, and carrier-carrier scattering. Each of these may have a major impact on the performance of the cell under certain operating conditions.

The Model

Physical Effects of Importance

One of the major advantages of a numerical model is that it affords one the opportunity to include the very large number of physical effects which may be acting simultaneously within a solar cell. The complexity of the phenomena and their interactions with each other preclude analytic solutions in anything except highly idealized situations, which are not indicative of actual cells or operating conditions. An attempt has been made in the formulation of SCAP1D and SCAP2D to include as many of the physical effects which are known to influence cell performance as possible and to do this in a manner which represents our

present knowledge of these effects. One of the goals in writing these codes was to have them be sufficiently accurate in their representations so that they could be used in a predictive mode. This is possible only if all of the pertinent physical effects are included.

In those cases where the physics is questionable, we have attempted to include options which allow one to choose between various models. For example, in the case of heavy doping effects, one is able to choose between the models of Slotboom, Lanyon-Tuft, and Mahan, or to supply a subroutine of one's own choosing.

We have attempted to choose materials parameters which in our estimation are the most reliable. These materials parameters are used as default values. The user can easily change these parameters to values that he views as more reasonable.

The following physical effects are included in the codes: hole and electron mobilities, including their doping and temperature dependencies; heavy doping effects, using the formulation of Lundstrom, Schwartz, and Gray; absorption coefficients, including their temperature dependence; recombination, including Auger, Hall-Shockley-Read, and surface recombination. Surface recombination is handled through the specification of the surface recombination velocity. In the case of SCAP2D, the effects of surface potentials are also included.

Semiconductor Equations

The programs perform a full simultaneous numerical solution of the two continuity equations and Poisson's equation subject to the boundary conditions appropriate to one and two-dimensional cells. The equations are formulated as shown in equations 1-3.

$$\nabla^2 v = -\frac{q}{\epsilon}(p - n + N_D - N_A), \tag{1}$$

$$\nabla \cdot \mathbf{J}_p = q(G - R), \tag{2}$$

$$\nabla \cdot \mathbf{J}_n = q(R - G). \tag{3}$$

The generation term in equations 2 and 3 are given by

$$G(x) = \int_0^\infty \Phi \alpha e^{-\alpha x} d\lambda \tag{4}$$

and the recombination term is given by equations 5, 6 and 7.

$$R = (pn - n_{ie}^2)\left[A_n n + A_p p + \frac{1}{\tau_n(p + p_1) + \tau_p(n + n_1)}\right] \tag{5}$$

$$\tau_p = \frac{\tau_{po}}{1 + \dfrac{(N_D + N_A)}{N_c}} \tag{6}$$

$$\tau_n = \frac{\tau_{no}}{1 + \dfrac{(N_D + N_A)}{N_c}} \tag{7}$$

The hole and electron current densities which appear in equations 2 and 3 are given by

$$J_p = -q\mu_p p\nabla v_p - kT\mu_p \nabla p \tag{8}$$

$$J_n = -q\mu_n n\nabla v_n + kT\mu_n \nabla n \tag{9}$$

$$v_p = v - (1-\gamma)\frac{\Delta_G}{q} \tag{10}$$

$$v_n = v + \gamma\frac{\Delta_G}{q} . \tag{11}$$

where v_p and v_n are the effective potentials defined in equations 10 and 11 and Δ_G and γ are parameters which account for variations in the band structure, such as density of states and band gap, and account for Fermi-Dirac statistics.

No low injection assumptions are made. The equations are solved from contact to contact with appropriate boundary conditions so that the solutions are valid for all ranges of operation and include minority and majority carrier flow. The latter places some restrictions on the CPU word size required for solution.

These codes have been extensively tested for accuracy by comparing the results of their predictions with experimental results obtained on very carefully and extensively characterized cells for a wide range of cell designs and operating conditions. The agreement has been such that a high degree of confidence has been developed in results computed using these codes.

Code Description

Figure 1 is a block diagram of the structure of SCAP1D and SCAP2D. The operator must supply information about the materials parameters, a description of the device to be analyzed, the type of analysis which he wishes to perform, and the spectrum, if appropriate. He also can, if he wishes, control some of the details of the numerical solution; the amount of information supplied while the program is converging to an answer and how the output information will be stored or displayed.

The results of the computation are presented in printed summary form and the detailed results of the calculation are stored on magnetic tape. A separate plotting routine is used to access the information on tape and to display the appropriate parameters. The plotting capability is one of the most valuable features of the code, in that it allows one to effectively have a microscopic view of most of the parameters of interest in the interior of the cell under operating conditions. We will show some of the available graphical output as we discuss the capabilities of the code. Table I shows the input control offered to the operator. In every case default parameters are specified if the operator chooses not to supply a parameter.

Table II contains a listing of plots which are available through the plotting program. In this case the operator specifies the type of plot which is required and the region of the cell for which he desires that plot. Most of the figures which follow were obtained directly from this plotting routine.

In addition to the reliability of the output, the utility of codes of this type will depend on their ease of use and efficiency of computation. For example, in a design mode, it is

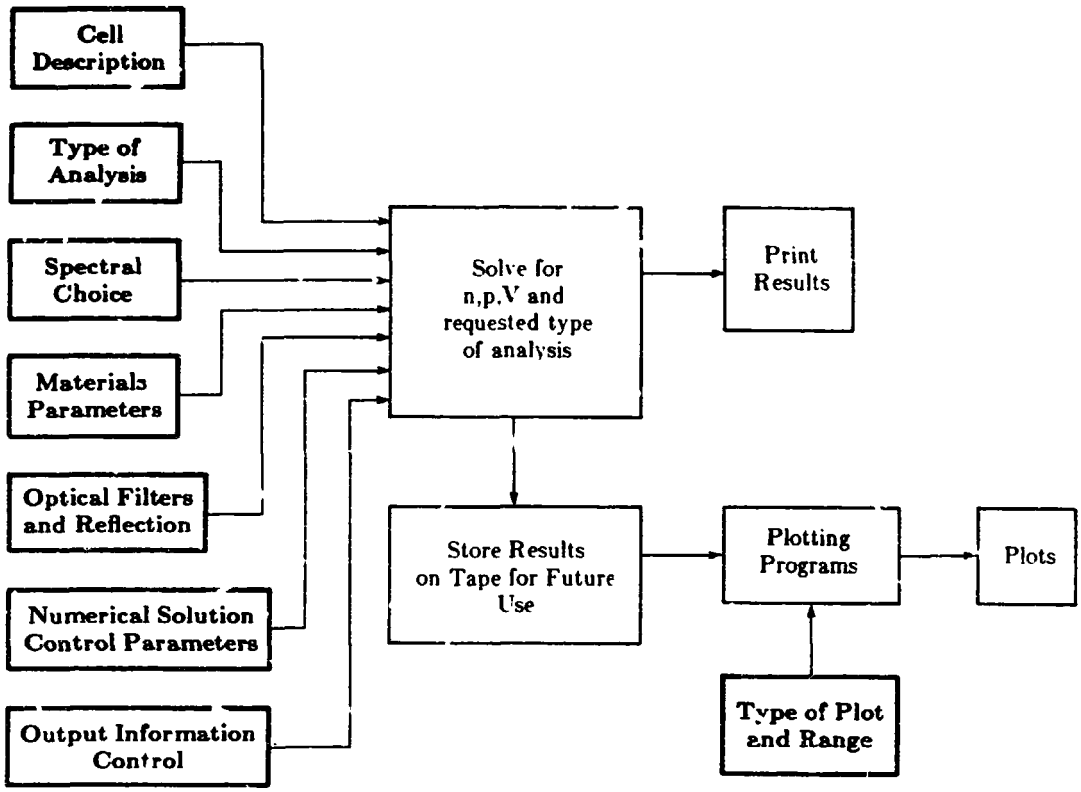

Figure 1 Block Diagram of the Structure of SCAP1D and SCAP2D

Table I - Input Parameters

Device Description
- Doping Profiles
  - Step junction
  - Erfc (N_s,x_j)
  - Experimental Profile
  - SUPREM II
- Dimensions

Materials Parameters
- Lifetime (τ and energy)
- Surface Recombination
- Auger
- Bandgap narrowing
  - Slotboom
  - Mahan
  - Lanyon-Tuft
  - User supplied

Spectral Choices
- AM 0
- AM 1.0
- AM 1.5 direct & global
- Monochromatic
- Uniform generation
- User supplied

Optical Filters & Reflection
- Filter (Ge, Si, SiO_2, GaAs)
- Back surface reflector

Types of Analysis
- Dark I-V
- Illuminated I-V
- Solar Cell
- Spectral Response

Table II - Plotting Options

Carrier concentration	Hole current density and components
Hole and electron current densities	Electron current density and components
Change in potential (from equilibrium)	Mobility
Doping density	Lifetime
Energy band diagram	Ratio of n_{ie}/n_{io}
Electric field	Potential
Hole and electron quasi-electric fields	Recombination rate
Effective fields (electric plus quasi-electric) for holes and electrons	Charge density
	Excess carrier concentration
Optical generation	

advantageous to be able to make multiple runs in a reasonable length of time and at reasonable cost. While SCAP1D can be run effectively on nearly any mainframe computer (a typical run on a CDC 6600 requires 100-300 CPU seconds), SCAP2D requires a very fast machine with a large amount of actual or virtual memory. On a Cyber 205, 300 CPU seconds are required for a typical run.

Situations Requiring Two-Dimensional Analysis

In many situations a one-dimensional simulation is quite adequate and there is no need to use the more complex and expensive two-dimensional simulation. On the other hand, there are a number of situations which only a two-dimensional simulation will suffice.

Some of the situations which require two-dimensional analysis are quite obvious, while others appear to be one-dimensional in nature, but, in fact, require a two-dimensional solution for proper description of the cell performance. Most of the cell structures which have been proposed as high efficiency silicon cells fall into the obviously two-dimensional analysis category. Among these structures are the Interdigitated Back Contact cell, the Vertical Multi-Junction cell, the Etched Multiple Vertical Junction cell, the Polka Dot cell, and the Grating cell. As an example of the use of SCAP2D in the analysis of these two-dimensional cells, we show figures 2 through 4 for an IBC cell. In Figure 2 we show the total short circuit current flow under one sun-conditions. In Figures 3 and 4 we show the majority and minority carrier flows for this same cell operating under the same condition.

Less obvious applications of the two-dimensional code are shown in Figures 5 through 6 in which a conventional solar cell has been analyzed. In Figure 5 we show the potential distribution along the emitter from a point half way between the grid lines up to the grid lines under open circuit conditions. This figure illustrates that there is a lateral voltage drop along the emitter, even under open circuit conditions, as a result of the current which is injected in the vicinity of the grid line. Figure 6 shows the circulating currents which exists in the vicinity of the grid line.

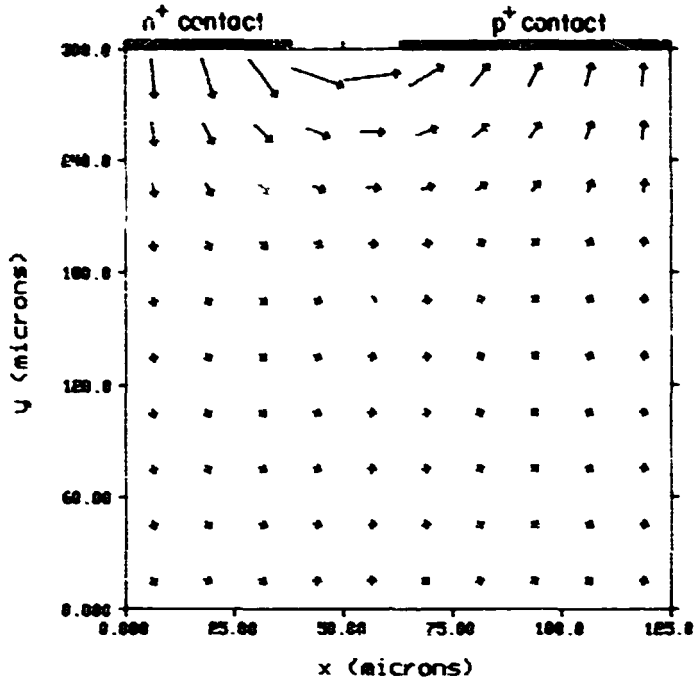

Figure 2 Total Short Circuit Current for an IBC Cell 1 Sun AM1.0

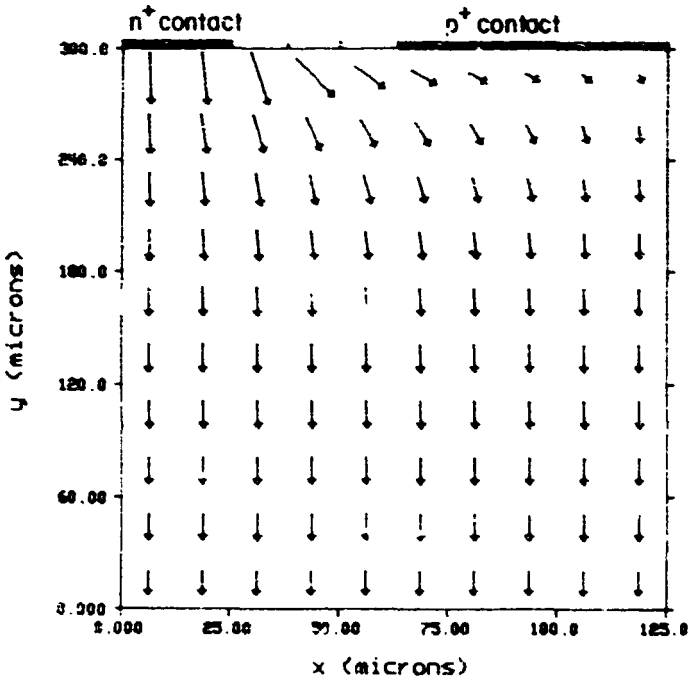

Figure 3 Majority Carrier Current Flow for the Cell of Figure 2

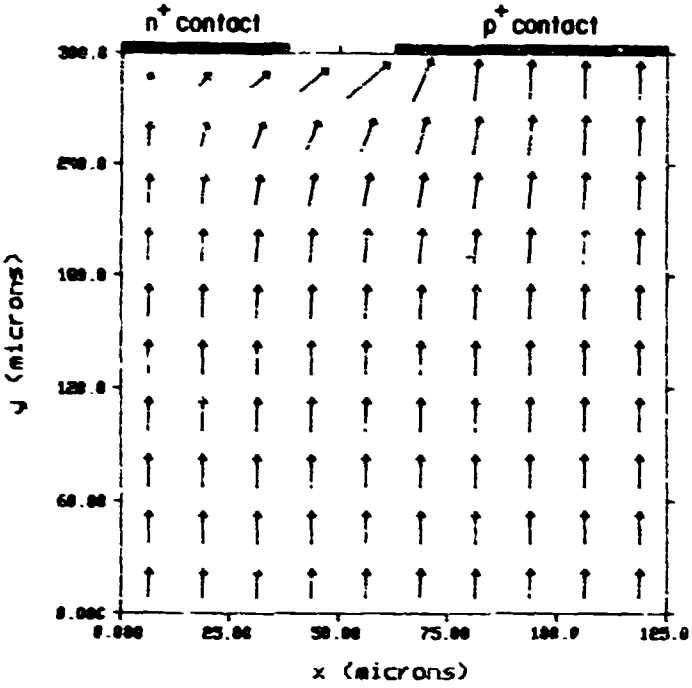

Figure 4 Minority Carrier Current Flow for the Cell of Figure 2

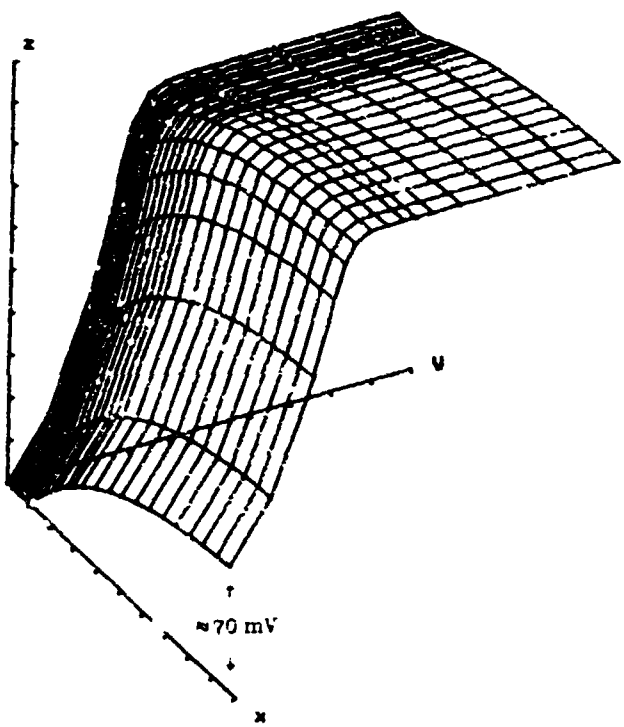

Figure 5 Potential Distribution in the Emitter of a Conventional Solar Cell Operating at 400 suns.

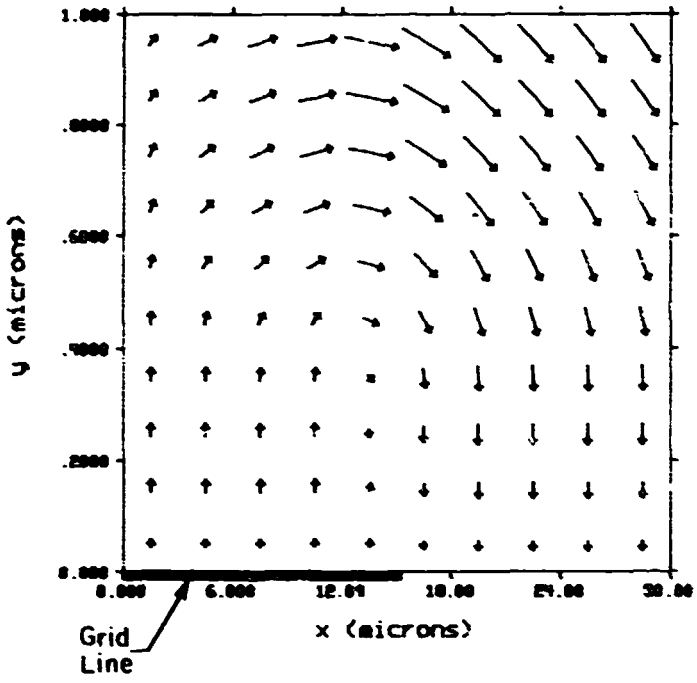

Figure 6 Circulating Current in the Vicinity of a Grid Line for a Conventional Solar Cell

An even less obvious problem with one-dimensional simulation occurs when one tries to properly model the front surface of a conventional cell. This surface is composed of a SiO_2-Si interface and a metal-semiconductor contact. In a one-dimensional simulation, one is forced to aggregate the two effects with some equivalent front surface recombination velocity, S_F. Figure 7 illustrates the difficulty with this approach. Under short-circuit conditions the proper value of S_F is equal to the surface recombination velocity of the SiO_2-Si interface. However, near open circuit conditions, the proper value of S_F may be 3 to 4 orders of magnitude larger. This is a result of the fact that the metal semiconductor contact may be a very effective recombination site for minority carriers. This is particularly important as the operating voltage of the cell increases. For proper operation of a one-dimensional code, the front surface recombination velocity should be a function of operating condition. The two-dimensional code does not have this problem, since the surface recombination velocity at the SiO_2-Si interface and the metal semiconductor interface are specified separately, and the recombination along the entire surface is properly accounted for under all operating conditions.

At high operating conditions, such as are found in concentrator solar cells, even the conventional cell behaves in a two-dimensional fashion and must be modeled using the two-dimensional code. Minority carrier current flow for a conventional cell operating at 800 suns is shown in Figure 8. If this cell is modeled using the one-dimensional code under these operating conditions, serious errors are encountered in the computation of the fill factor which can not be compensated for by including an external series resistance in the model, as the effect is nonlinear.

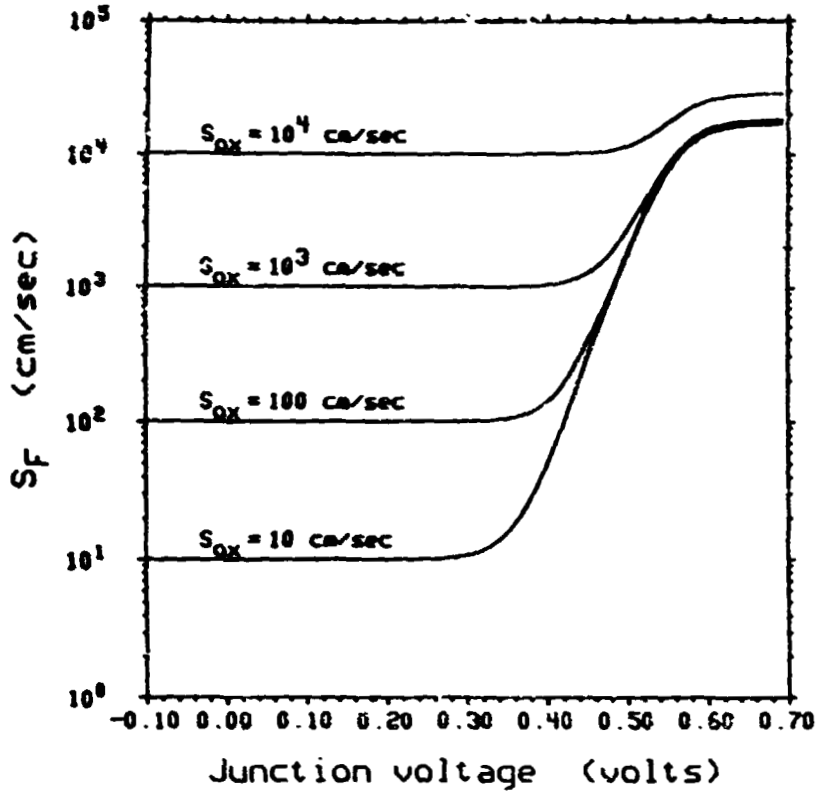

Figure 7 Effective Surface Recombination Velocity as a Function of Operating Voltage and the SiO_2-Si Surface Recombination Velocity

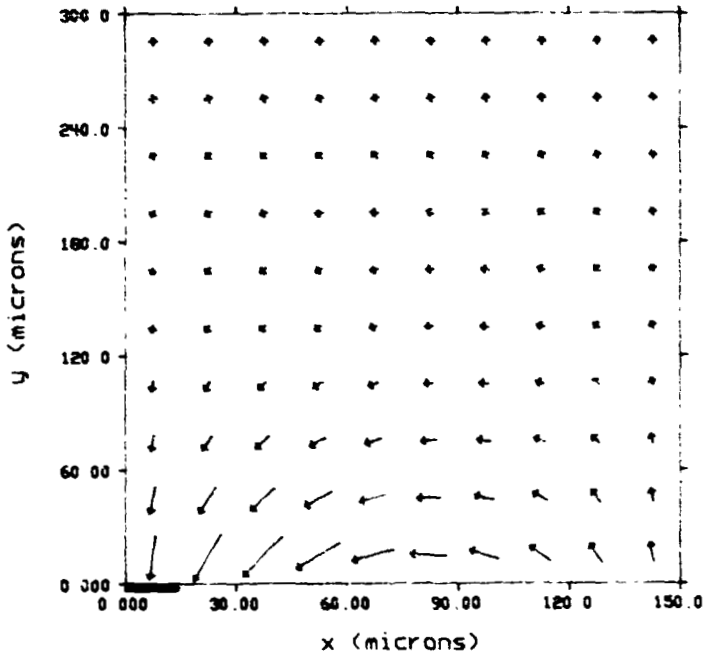

Figure 8 Minority Carrier Current Flow for a Conventional Solar Cell Operating at 800 Suns (V=.600 volts J=21.6 amp/cm^2)

Modes of Utilization

As we mentioned previously, a carefully prepared solar cell model is useful in a number of modes. In this section we will discuss the use of SCAP1D and SCAP2D as a design tool, a sensitivity analysis tool, an aid in the analysis of experimental data, an aid in the provision of insight into the operation of the cell, and, finally, as a predictive tool for the comparison of proposed cell designs and as a means of projecting performance as various technological barriers are removed. For the sake of continuity, we have chosen to use the Sandia high concentration cell operating at 1 sun as a base line design. This is a cell which has exhibited 18% conversion efficiency at one sun, and 20% conversion efficiency in the 50-100 sun range for an AM 1.0 spectrum.

Design

As a simple example we show, in Table III, the effects of variations in the base doping about the present design doping of 2.29×10^{16}, on the performance of this cell. We see that the present base doping is nearly optimum for the design parameters used in the other parts of the cell.

Table III

Solar Cell Performance Dependence on Base Doping
AM 1.0 (one sun)

Base Doping cm^{-3}	V_{oc} volts	J_{sc} ma/cm^2	F.F.	Efficiency %
5×10^{15}	.634	35.1	.828	18.35
1×10^{16}	.640	34.8	.833	18.46
2.29×10^{16}	.649	34.4	.836	18.55
1×10^{17}	.656	33.3	.838	18.21
5×10^{17}	.650	30.2	.836	16.37

Sensitivity Analysis

By utilizing a computer code such as SUPREM to simulate fabrication conditions one can model the sensitivity of device performance to fabrication parameters. Here, as an extreme case, we examine the effects of changes in the emitter doping profile on cell performance. The Sandia cell was simulated using the two emitter profiles shown in Figure 9. In Table IV, a comparison of these simulations is shown. Note that the erfc emitter profile simulation predicts a higher V_{oc}. This is due to the lower net recombination in the emitter as compared to the SUPREM II emitter profile simulation, as shown in Figure 10. Recombination is higher in the SUPREM II emitter because the doping is higher over most of the emitter volume, and therefore Auger recombination is correspondingly higher also.

If the results of a process simulation program such as SUPREM are coupled with SCAP1D or SCAP2D as shown above the sensitivity of the cell to process variations can be readily established.

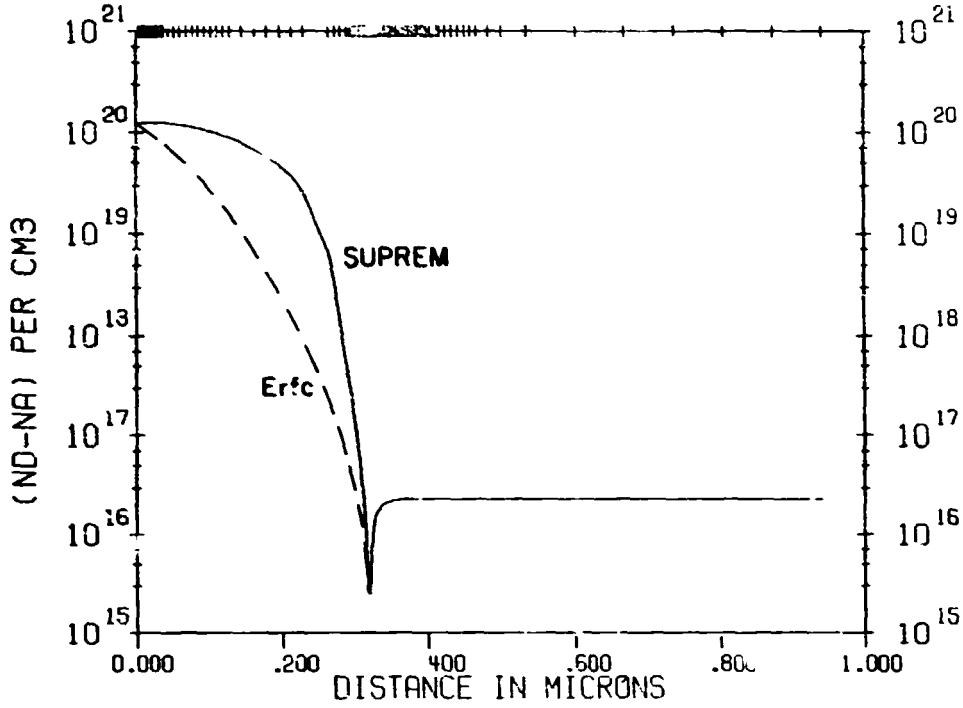

Figure 9 Emitter Doping Profiles as Determined by SUPREM II and Complimentary Error Function

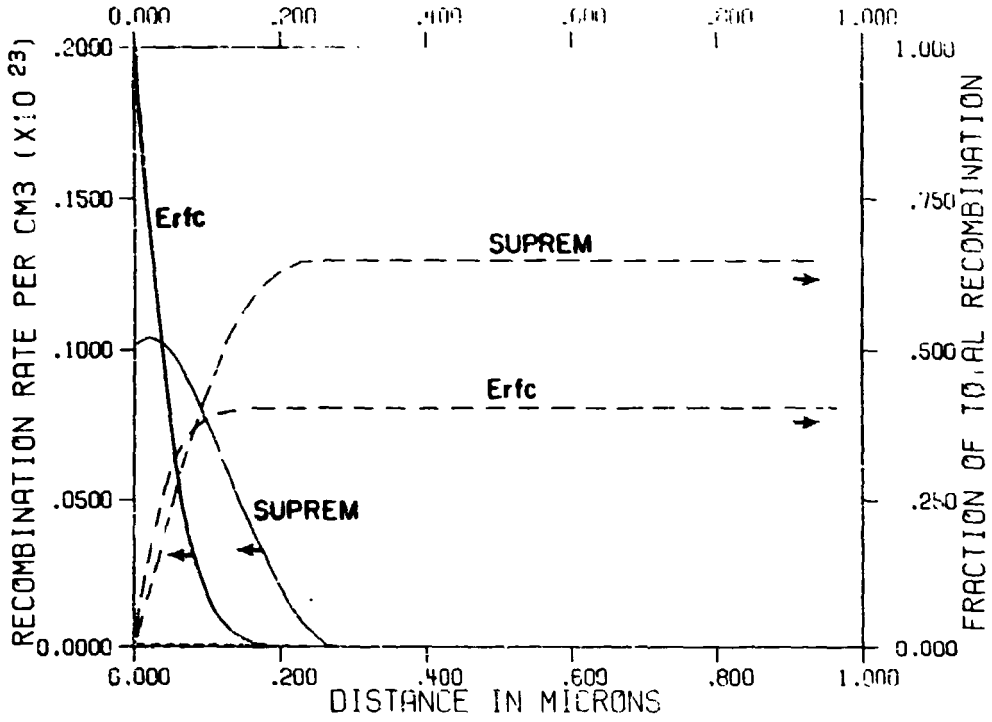

Figure 10 Emitter Recombination for the Two Doping Profiles Shown in Figure 9

Table IV

Dependence of cell performance on emitter doping profile
AM 1.0 (one sun)

Type of Profile	V_{oc} volts	J_{sc} ma/cm^2	FF	Efficiency %
Erfc	.648	34.3	.836	18.6
SUPREM II	.632	33.9	.833	17.75

Analysis

It is possible, by adjusting the parameters entered into the code, to obtain a fit between the model generated results and experimental dark I-V, solar cell, and spectral response curves. If this fit can be obtained for a single set of parameters, then one has a reasonable expectation that these are the correct parameters describing this device.

Insight

With the ability to observe most of the parameters of interest as a function of position and operating conditions anywhere within the cell, it is possible to achieve a great deal of insight into the limiting factors on any cell design. Examination of the model for the 20% Sandia cell very quickly establishes that the cell appears to be emitter limited, and, in fact, that further efforts in improving the performance of the cell should be devoted to reduction of the metal-semiconductor contact recombination and in reducing the volume of the heavily doped emitter.

Prediction

Potentially one of the most valuable, and also one of the most risky, uses of the numerical models is as a predictive tool. The models have already been shown to be quite reliable in comparing the relative merits of different cell designs. One particularly attractive way to utilize the code is to use it to identify limiting phenomenon in a particular cell design and then to remove that limitation and observe the effect on cell performance. In this fashion, one can predict benefits which will accrue through various advances in technology, and, in fact, can make some reasonable estimates of the ultimate performance of silicon single crystal solar cells. This latter use of the code is particularly risky since as the performance of the cell improves, physical effects which may have been insignificant in their effect on cell performance before, may suddenly become the dominant limitation.

Problem Areas

There are a number of areas in which there is concern about existing solar cell models either because the physics is not well understood, available data is thought to be unreliable, or because the effect has not been include in the model. These areas of concern are discussed below.

Heavy Doping Effects

There is a controversy over the origins and magnitude of heavy doping effects. There is a great deal of scatter in the measured effective band gap narrowing, particularly in the very heavily doped samples where we have our major concern. In order to alleviate this situation somewhat, we have provided the operator with the option to choose between most of the popular band gap narrowing models. This remains an area of major concern and is probably the least reliable area in the modeling of silicon solar cells.

Auger Recombination

Some uncertainty exists about the reliability of published Auger coefficients. At least two groups (Sandia and General Electric) have indicated that published Auger coefficients may be too large.

Minority Carrier Mobility

Reliable measurements of minority carrier mobility do not exist. Various authors have proposed that the minority carrier mobility is larger, smaller, and the same as the majority carrier mobilities of the same type carrier. As a consequence, SCAP1D and SCAP2D assume that the minority carrier mobilities for electrons are the same as they would be if electrons were majority carriers. A similar assumption is made for holes.

Metal-Semiconductor Contacts

In well designed high efficiency solar cells, the metal semiconductor contact limits the open-circuit voltage. The removal of this high dark current source, through the use of tunneling contacts or through the reduction of the metal-semiconductor contact area, has already demonstrated a significant improvement in open-circuit voltage. Further advances in this area may well employ heterojunction structures in addition to the present tunneling structures. SCAP1D and SCAP2D allow for specification of a finite minority carrier surface recombination velocity to model this effect.

Doping Profiles

We have already seen that device performance can be a strong function of the shape of the emitter doping profile. SCAP1D and SCAP2D allow for the use of a complimentary error function, a computed profile based on the Fair diffusion model for phosphorus, doping profiles obtained from a process simulation program such as SUPREM, or experimental data. The use of data from SIMS measurements has the problem that it includes the total impurity concentration not just the electrically active dopants. If any precipitation is present in the highly doped region, SIMS will overestimate the amount of active dopant. Spreading resistance measurements are a measure of the free carrier concentration. Near the depletion region this can lead to significant errors in the doping profile if the spreading resistance profile is interpretated as being the same as the doping profile.

Spectral Response

Spectral response measurements are particularly useful for obtaining information about the base lifetime and the surface recombination velocity. However, some difficulty is experienced in matching long wavelength response with computed response. This difficulty has been traced to the fact that small changes in device temperature can lead to large changes in the long wavelength response as a result of changes in the absorption coefficients due to a shift in the band edge.

In order the determine the surface recombination velocity of the SiO_2–Si interface, it is also highly desirable to have spectral response measurements in the very high absorption regime of .35 - .4 μm. Accurate measurements of the internal quantum efficiencies are difficult to obtain at these wavelengths.

Effects of Band Gap Narrowing on Long Wave Length Absorption Coefficients

At the present time no corrections for the effect of band gap narrowing are made to the absorption coefficients.

Carrier-Carrier Scattering

Carrier-carrier scattering can be a significant effect in high concentration solar cells, and will become a significant effect in one sun solar cells as the efficiency is increased.

High Injection Lifetime

At the present time very little data is available on majority carrier lifetime. A typical modeling approach is to assume that the majority carrier lifetime is the same as minority carrier lifetime. This seems to give reasonably good agreement with cell performance under high injection conditions, but direct measurement of the high injection lifetime would be highly desirable.

Conclusions

One and two-dimensional device models have been quite successfully employed as an aid to design, interpretation, sensitivity analysis, and prediction. However, the predictive capability of any device code is only as good as the physics which is modeled and the data which is supplied. If further improvements are to be made in the performance of single crystal silicon solar cells, careful attention will have to be paid to both of these areas and a great deal of effort will have to be devoted to measurement techniques which will allow the independent determination of the parameters which must be supplied to the device code.

Acknowledgment

SCAP1D and SCAP2D were developed under the sponsorship of Sandia National Laboratories on contract number 52-5675.

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SAH: I would like to ask you about that particular example you gave, the complementary error function, also the SUPREM. There is quite a difference in the results. What is the basic mechanism? What are the recombination mechanisms that give you the difference?

SCHWARTZ: What's included in the code is Hall-Shockley-Read and Auger using Schmidt Auger coefficients, and for that particular run -- thank you for asking -- I should have mentioned at the time: for that particular run we used the Slot-Boom band-gap narrowing model, so there is a significant amount of band-gap narrowing occurring, and recombination mechanisms. For that particular run, Auger and Hall-Shockley-Read, and I didn't bring the plot along. The plot shows the split between them. I don't recall what the split was.

SAH: For the particular profile, was it the Auger that causes the one to be better than the other one?

SCHWARTZ: Yes, I believe that it was Auger, but I don't have the plot with me.

NEUGROSCHEL: You said that the published Auger coefficients don't agree with the experiment. In order to get agreement, do you need larger lifetimes or shorter lifetimes?

SCHWARTZ: The recombination wants to be reduced. I should qualify that a little bit. I was repeating what is said in a couple of publications by Posene at GE and Weaver at Sandia. It is possible that the problem lies in the band-gap narrowing model and not in Auger, so one wants to be a little careful. There is a problem in the emitter, and that's clear, and people have tended to blame Auger. I guess I'm not completely convinced that it is Auger -- it may well be related more to the band-gap narrowing.

DAUL: I would like to follow up on Sah's question. You have the same carrier density at the surface for the SUPREM and for error function. So, normally you have much larger field right at the surface in case of complementary function, and I would expect less recombination there. Would you give some reason why?

SCHWARTZ: Yes. There are a number of reasons. One is that the recombination rate only depends on the Auger coefficients and lifetime, but also on the excess minority carrier concentration, and if I had shown the plot, what you would have seen is that many of the carriers are recombining in the case of SUPREM as they moved, and the axis cure was lower at the surface. The other difference is in the way that the band-gap narrowing effective field is distributed. The minority carriers in the emitter don't see just an electrostatic driving force due to the gradient. There is another component, which is associated with band-gap narrowing itself, and it tends to reduce the effect of pulling minority carriers away from that surface or keeping them out of the emitter. Both are operating and they are distributed differently.

DAUD: The second question has to do with actually running this program. We find that one of the items that one has to put in is the τ_{p0} and τ_{n0}. Normally when we measure, we either measure the lifetime or diffusion length where the doping is already there. How does one reconcile with this? What kind of numbers one should put for τ_{p0} τ_{n0}?

SCHWARTZ: I'm sorry. You say you normally measure what?

DAUD: Say we have a cell where we measure the diffusion length or the lifetime. We cannot directly put that in your model because your model corrects it for the doping.

SCHWARTZ: Yes. There were a lot of features that were not talked about here, and since we have sent a copy of the code out to JPL, he is asking. You have the option of turning on what amounts to a Kandel fit to doping. If in fact you have that turned on and if the base doping is above the transition doping for the the Kandel fit, then you have to correct that. If you have measured the lifetime at that particular doping level, you either have to correct it or just turn Kandel fit off and enter the value you measure. It's your choice. It is under your control on the input deck.

LINDHOLM: I have three questions. They are all, I think, fairly quick. Just to remind the audience: you recast some of the -- what you might say, equations which were truer to the physics -- into a form that one is more used to seeing in a conventional treatment of semiconductor device physics. In so doing, you introduce the parameter that you called small gamma, lower case gamma, and I think that that parameter was supposed to have taken care of various things that were being violated by the density of states. You made a big point, which is an extremely valid point -- that the parameters that go into the model have to be measurable. So with that preparation for the audience, I could have just asked you what success have you had in measuring gamma, and how do you do it? How don't you do it, if you can't do it?

SCHWARTZ: I tried to stay away from the equations, Fred, and I apologize for the poor quality here. The gamma that Fred is talking about entered into the effective potential that we showed. Here is the electrostatic potential, and here is the term which I said was an effective asymmetry factor, and that term is not normally known. As one gets measurement of the effective band-gap narrowing, which in fact looks like this -- the band gap plus all the degeneracy and band structure effects. Gamma, in fact, has electron affinity divided by the delta G minus terms for degeneracy. The answer to your question is, you don't know. But before I let that go, it turns out that for solar cells you seldom care, and the reason for that is the following: GE observed this first, the range on that numbers from 0 to 1 and one can run the full range and see almost no detectable change in the device characteristics. On the other hand, if you look inside the device, there are radical differences in the electric field distribution in the emitter, in that region. There are huge differences. But it turns out, and you can do this in closed form, that if you are dealing with a region which is quasi-neutral and low injection, as the

emitter is under anything except extreme conditions, you can show in analytic form that, in fact, terminal characteristic is independent of that parameter. There are places where it makes a difference. It does make a difference in junction capacitance: you can show that fairly readily. It makes a difference in the electric field. And a dramatic one if, for instance, you are concerned with avalanche, not in a solar cell, but calculations of avalanche, and you are in a heavily doped condition. Then possibly one should be worried about present-day avalanche coefficients if they are based on classically calculated electric fields. But the answer is that it doesn't affect the terminal characteristics.

LINDHOLM: The reason I asked that is twofold. First of all it would seem to me that for diagnostic purposes it would be desirable to know what you call gamma, or what I would rather just call the electro. finity, and I know about the comment you made about the quasi-neutral region. But as you start entering a little bit into the junction transition region, then I think it becomes more important. And the reason I asked that is, if I correctly read your earlier paper with Mark Lundstrom, that you indicated a method for measuring gamma. And so I come back to my original question: what degree of success have you had in measuring gamma?

SCHWARTZ: Very little. We're still working on it.

LINDHOLM: I think it is a good thing to work on, actually. The reason is that it's very easy, even though you did not intend to do this -- in fact, your wording was very careful -- but people will take sort of ... ial cases and say it doesn't matter, but it does matter from a diagnostic point of view in finding out what's going on with the profiles,how you can improve the device, that kind of thing. I'm very glad you used such careful wording, so congratulations on that.

SCHWARTZ: I'm glad you read the paper, very few people have.

LINDHOLM: Its a very interesting and very good paper. I was extremely interested in your measurement of gamma.

SCHWARTZ: I have a Ph.D. student who is extremely interested too.

LINDHOLM: The other thing that I noted that you said, and since you word things so carefully, I was noticing that you said that most of the people who made electrical measurements in effect were measuring the p-n product. Now, I think that that's probably true of the Slot-Boom graph you use, the transistor structure; I think it's not true of ERIC people. Would you agree with that? A good portion of the data now coming out is EBIC data and the guys from GE who aren't here are talking about p-n product and I think that they can't do that. The fundamental reason is that Fermi levels have to remain sensibly, spatially invariant over a significant region of the device in order for that measurement to yield the p-n product.

SCHWARTZ: That's absolutely right, and from a physics point of view is very pleasing. And from a modeling point of view it's difficult, because now

in the intermediate region, where one worries about what happens to the band shape, you've got a problem in using it.

LINDHOLM: One last one. You keep mentioning two-dimensional programs, and I would like to know about three-dimensional programs, and why you can get away with two-dimensional.

SCHWARTZ: It's not so much getting away with two-dimensional, it's really a level of difficulty. In our case -- one thing I didn't mention, and I neglected it inadvertently -- I told you that it cost about $5.00 and takes 100 to 300 seconds on a 6500 CDC if you run the 1-D code. It takes about 300 CPU/second on our CYBER 205 Supercomputer to run the 2-D code. Now, what I mean by that is to run a full analysis, something like 10 points, and do all the associated stuff. That uses about 2,000 mesh points. So right now it's about what we are capable of tackling. If Purdue will put another two million words into the main memory of that computer then we will look at the three-dimensional.

LINDHOLM: If the next speaker is successful in cutting the computer time significantly by his technique, as he suggests, would you then strongly advocate three-dimensional steady-state modeling as a highly useful, moderately useful or rarely useful vehicle for solar cell design optimization and for monitoring manufacturing processes?

SCHWARTZ: I think that's a very good question, whether it's asked about one, two or three-dimensional, and the answer lies in how easy it is to use, whether it's fast, are the turn-arounds quick, and what is reasonably cheap. Because you do have to make a lot of runs, and if it's very expensive or very time-consuming, the utility becomes a lot less.

LINDHOLM: Suppose it doesn't cost anything?

SCHWARTZ: Then its very useful to do even for one sun. Is that what you think?

LINDHOLM: I haven't thought enough about it.

SCHWARTZ. If you want to do a cell like Dick Swanson's.

LINDHOLM: A more conventional cell is very useful there? Or is it moderately useful?

SCHWARTZ: I doubt it, I can't see the benefit to a conventional cell with three dimensions.

QUESTION: Dick, a quick question. Did you decide that radiative recombination and trap Auger effect could be neglected safely?

SCHWARTZ: No, we didn't. I told you the status of the code as it was. It is a fairly straightforward matter to add those components to it, we just haven't driven things, we haven't made any runs where the other lifetime-limiting mechanisms were low enough to do that. But clearly, if you do, that's a limiting mechanism that is not present and needs to be added.

QUESTION: And on the surface recombination you might also have trap Auger effects, or do you wrap it all up in a surface recombination velocity?

SCHWARTZ: Well in the one-dimensional code it's wrapped up in the surface recombination velocity. I didn't talk about how it's handled in two dimensions. In two dimensions you could either do it by integrating through the trap states and capture cross-sections, or you could do it by a lumped parameter, which is probably not as good -- and you do have to control surface potential, which we do by setting the charge in the oxide.

QUESTION: Now, a last question: capacitance. Do you work it out or do you do current-voltage, capacitance voltage?

SCHWARTZ: No, JPL doesn't know if their version of the code does have capacitance in it, we just didn't tell them. It is the equivalent of very low-frequency capacitance I'll tell you what it is and you can name it. It is the integral of either the electrons or holes with the appropriate voltage term put in, and you are quite right.

QUESTION: It can miss by a factor of three or four?

SCHWARTZ: Yes. We don't use it that way.